SANDIFUR

Radiometric Action of Light
And Heat on Suspended
Gold Leaves In High Vacua

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RADIOMETRIC ACTION OF LIGHT AND HEAT ON SUSPENDED GOLD LEAVES IN HIGH VACUA

BY

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A. B. Indiana University, 1906

THESIS

Submitted in Partial Fulfillment of the Requirements for the

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IN

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May 15, 1909

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

CLAUDE WILLIAMSON SANDIFUR

ENTITLED RADIOMETRIC ACTION OF LIGHT AND HEAT ON SUSPENDED GOLD LEAVES IN HIGH VACUA

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Master of Arts in Physics

Chas. T. Knipp
In Charge of Major Work

A. P. Carman
Head of Department

Recommendation concurred in:

Committee on Final Examination

In an article by J.T. Bottomley and F.A. King[1] entitled "Experiments with Vacuum Gold-leaf Electroscopes on the Mechanical Temperature Effects in Rarefied Gases", attention is called to the action of gold leaves in a highly exhausted vessel when subjected to radiant heat and light.

They explain that the observations were the result of an attempt to increase the degree of exhaustion of a radium "clock" by use of the Bunsen burner. The radium clock[2] consists of a highly exhausted vessel in which are two gold leaves hanging parallel and close together with a bit of radio-active material above. The leaves, charged by the action of the radio-active substance, diverge until they strike earthed conductors on the sides of the containing vessel, when they are discharged and fall together.

By chance the Bunsen burner was left standing near the clock, and it was observed that the leaves no longer struck as before but that the one away from the flame struck first, and that the leaves, instead of hanging symmetrically as before, hung thus:

A soldering bolt was found to produce the same effect through a range of temperature from a little above that of an ordinary room to that of the white hot bolt. The presence of the hand affected the leaves as did also different sources of heat and light, such as an alcohol flame, a Nernst lamp, etc. A test tube of water frozen in liquid air produced an attraction of the leaves, an effect which is the reverse of that of the warm bodies.

[1] Proceedings of the Royal Society, June 8, 1907, Ser. A, Vol. 79.

[2] Strutt, Phil. Mag. November, 1903.

To be sure that the effects observed were not electrical, the clock was covered with wire gauze which was earthed, and, although electrified rods of glass and sealing wax produced no visible effect, the action of the hot and cold bodies was but little diminished. A delicate thermojunction used to explore the region about the clock showed that marked effects could be produced on the gold leaves by temperatures which the junction could scarcely detect.

They made a special electroscope for the purpose of eliminating all electrical effects. Its especial feature was a conducting (lead foil) cover for a large part of the outside of the case which was electrically connected with the leaves and with earth. The precautions taken and the curious shapes given the leaves prove that the effects were not electrical.

My attention was called to the above report by Professor A.P. Carman, who suggested that I do the experiment because it was peculiarly interesting and because it might furnish the basis for further research.

In order to become familiar with this kind of work, I tried out the various kinds of air pumps in the laboratory. I also spent considerable time in an unsuccessful effort to construct a manometer that would measure the pressures obtained. At the time there was no McLead gauge in the laboratory.

Since the pressure mentioned by Bottomley was 1/20 millionth of an atmosphere, it was soon found that the oil immersion pumps would not do. The highest exhaustion obtained with them was 0.02 mm. mercury pressure. The Toepler valveless form of mercury pump was next tried with better results. But it required a great amount of time and labor. When sealed directly to a 500 cc. McLeod gauge (see Plate I, Fig. 2), it gave a pressure of 0.011 mm., as measured by

the gauge, after four hours pumping. The pressure did not change perceptibly during the 48 hrs., for which the system was left standing. One half hour additional pumping brought the reading to 0.009 mm. Running the pump 3 hrs, longer reduced the pressure to 0.005 mm. below which no amount of pumping would force it. The trouble was that the very small bubble of air, resulting from many strokes when the pressure was so low, clung to the walls of the capillary exhaust tube and could not be expelled. It often disappeared completely after being forced a short distance down the tube, only to reappear at the top a little later.

The pump next tried was the Gaede rotary mercury pump[1]. See Plate I, Fig. 1. When this pump was attached to the 500 cc. McLeod gauge with a preliminary exhaustion of 1.8 cm. produced by a motor driven "Geryk", the following readings were taken.

Table I.

	Time	pressure tube	volume tube	pressure
	10:00	-----------	-----------	1.8 cm.
a.m.	10:01	21.4 cm.	0.053 cc.	0.26 mm.
	10:03	-----------	-----------	0.02 "
	10:06	9.2 "	0.03 "	0.006 "
	10:15	15.0 "	0.01 "	0.003 "
	10:50	11.0 "	0.01 "	0.0022 "
	11:50	1.7 "	0.01 "	0.0017 "

The system was left standing until 5:00 p.m. to test for leaks. The reading showed a small increase in the pressure, which might have been due to gas given out by the walls of the gauge, or to a leak. At 5:30 p.m. pumping was continued as indicated in table II.

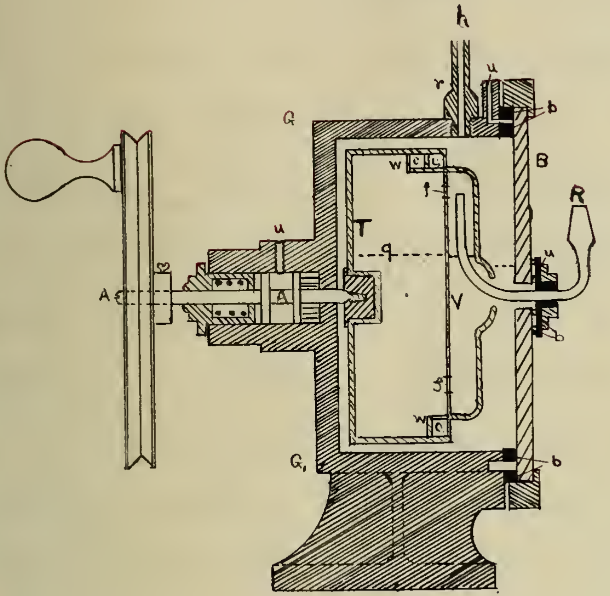
Table II.

	Time	pressure tube	volume tube	pressure
	5:30	11.0 cm.	0.01 cc.	0.0022 mm.
p.m.	5:32	3.0 "	0.01 "	0.0006 "
	5:35	2.5 "	0.01 "	0.0005 "
	5:38	2.2 "	0.01 "	0.00044 "
	5:42	2.0 "	0.01 "	0.0004 "

1 Phys. Zeitschr., vol. 6, pp. 758-760, November 9, 1905.

Plate I.

Figure 1.



Gaede Pump
Side View.

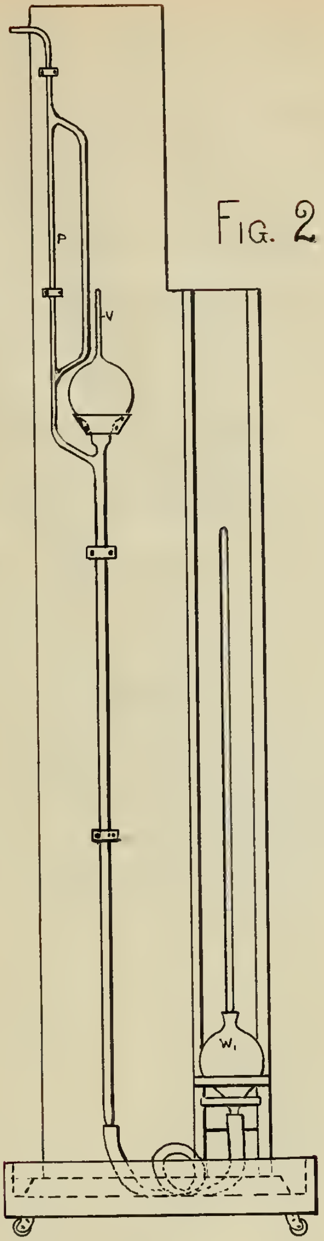
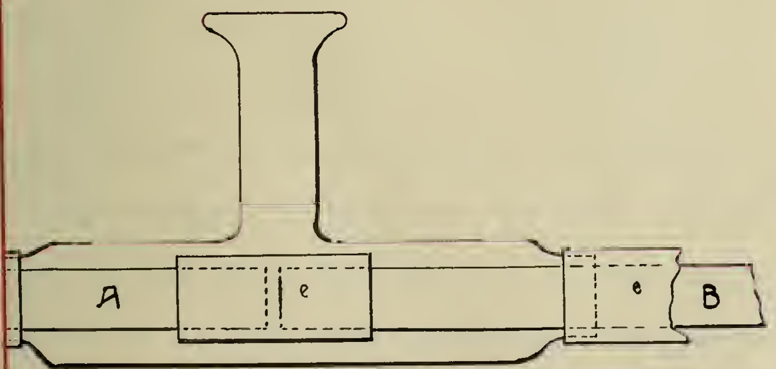


Fig. 2.

McLeod Guage.

Fig. 3.



Horizontal Seal

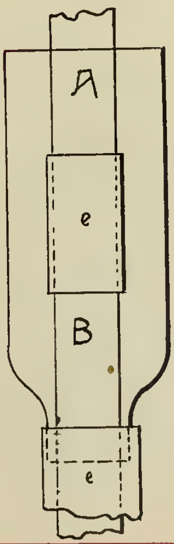


Fig. 4.

Vertical Seal.

Although pumping was continued for more than an hour, there was no change in the degree of exhaustion. Probably the rate of exhaustion was offset by the rate of leak, and by the gas that was given off from the walls of the vessel where it had condensed. The system was left until 7.00 next morning, when the pressure was 0.004 mm., a change that indicates a leak. This difference (0.0036 mm.) divided by the time gives a leak of 0.000004 mm. per minute for the interval. The rate of leak may have been slowly increasing, for during the next two hours it figured 0.00003 mm. per minute. The only seals in the system were those in the manometer portion of the Gaede pump. They were ground glass lubricated with vaseline.

At 10.52 a.m. the pump was started again, but for some reason the pressure at starting was not recorded. It can be found from the rate of leak given. The readings were as follows:

Table III.

Time	pressure tube	volume tube	pressure
10.52	--------	--------	------
10.54	11.5 cm.	0.01 cc.	0.00023 mm.
10.58	8.0 "	0.01 "	0.00016 "
11.00	6.0 "	0.01 "	0.00008 "

Continued pumping did not improve the vacuum. The Gaede is the pump used in all subsequent work. The system was left standing for several days to test for a leak. In the meantime the rubber tube connecting the mercury well to the gauge proper burst and a large amount of mercury spilled. After repairing the tube I returned to the well the mercury in the base of the gauge support. But a part of it had been gathered from the floor by a student working in the same room, and thus dirt was introduced into the gauge. It soon began showing as dark bands on the glass surface where the mercury was left standing for any considerable time. How much it vitiated

the readings of the gauge I could not tell.

The 500 cc. gauge used was made by Max Kohl, Germany. The pressure tube was graduated in millimeters, while the volume tube had 0.002 cc. divisions from zero to 0.14 cc. The 0.01 cc. division on the volume tube was opposite zero on the pressure tube, so that for any volume other than 0.01 cc. the reading on the pressure tube had to be corrected. This correction was easily made since each 0.002 division was 0.935 mm. To find the pressure measured, multiply the corrected pressure reading by the ratio of the reading on the volume tube to 500 cc. The range of the gauge was from 0.1 mm. to 0.000004 mm. mercury pressure, although later it will be shown that it is not accurate for pressures less than 0.0001 mm.

The next step in the work was the construction of a suitable electroscope for the experiment. The details of the construction were left to the shop mechanician. The case (see Plate II) was made of brass tubing 7 cm. in diameter and 9 cm. long. The top and bottom were of sheet brass turned with a shoulder as shown and were soldered in. There were 4 windows at angles of 90°. Each had a 1.5 cm. circular opening, that was closed with glass cut from microscope slides. In Plate II, Fig. 2 is a view looking down on the top, while Fig. 1 is a section made by a plane cutting on the line NM. G (Fig. 1) shows the method of supporting the gold leaf. It was the intention either to polish or to lamp black the part of the support behind the leaf, whichever experiment might prove to be better. R is hard rubber into which the stem of G has been tightly fitted; the lower surface was polished to seat on the case. E (Fig. 2) is the exhaust nipple. All joints not soldered were sealed with De Kotinsky's cement. This vessel was connected to a glass tube from the Gaede pump by a mercury seal such as is shown in Plate I, Fig. 3.

Plate II.

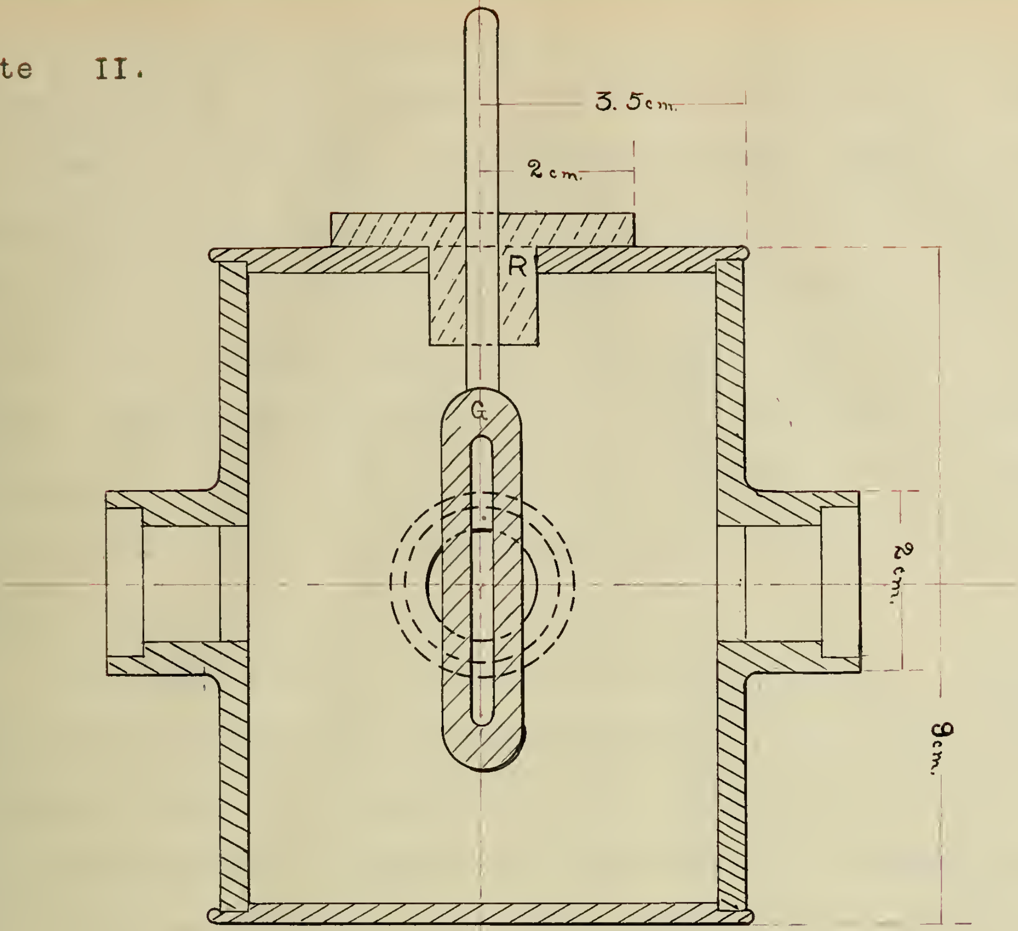


Fig. 1

ELECTROSCOPE.

Métal Case.

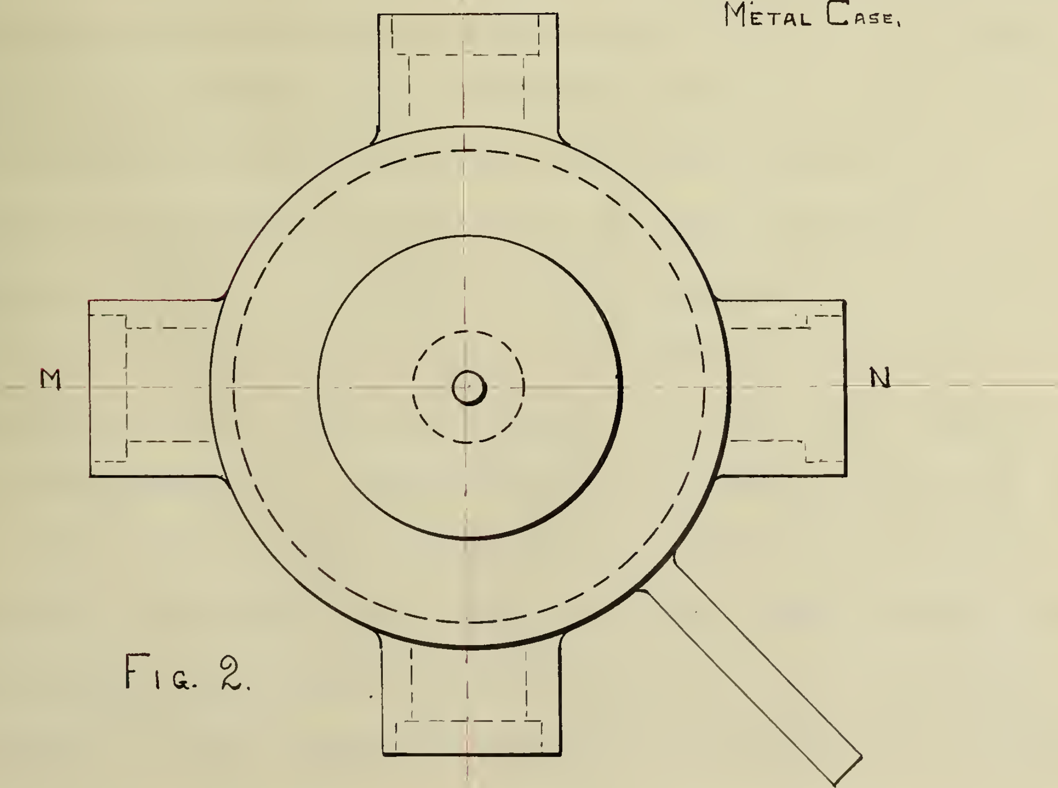


Fig. 2.

A few minutes pumping were enough to show that the electroscope was going to give trouble. The next six weeks were spent in an effort to make it hold air. The soldered joints leaked and had to be resoldered. The cement had the annoying habit of loosening just when one felt sure that it was going to hold. Its letting loose was probably due to the unequal expansion of the metal and of the rubber or glass with temperature changes. There was some ground for believing that the walls of the vessel, especially the hard rubber, allowed the air to pass in slowly. My experience showed that soldered or cemented joints should be avoided where possible.

The final effort to make the electroscope hold was a repeated immersion of the vessel in melted paraffin. When cool the windows were cleaned, and it was immersed again. This was continued until as many as twenty layers covered the electroscope. Although not successful, this method was a great help. The lowest pressure obtained with this vessel was 0.0014 mm., and that for only a very brief time.

During all this experimenting, the Gaede pump was loosing in efficiency, and the mercury surface and drum bore evidence of the presence of considerable dirt. This pump consists of an iron vessel, half filled with mercury, in which a porcelain drum rotates. During the rotation the chambers into which the drum is divided are filled alternately with air and mercury. These chambers at first suck the air from the receiver and during further rotation expel it. Fig. 1, Plate I, shows a side view of the pump. G is the cast iron casing with a strong base G_1. The front of the casing is closed by the glass plate B, 2 cm. thick, which is fastened to the casing by means of the cast iron ring P and 5 bolts and nuts. The U-shaped tube R passes through the central hole in the glass plate and connects the front space V of the drum with a receiver attached to R. The pump is

filled with mercury up to the line q. The axis A passes through a mercury stuffing box into the casing and carries the drum T. r is a steel tube screwed into the casing and fitted with ends adopted to take rubber tubing, and with the steel cock h. The glass disc B is made air tight against the casing and the tube R by means of two concentric rubber rings b, the space between which is filled with mercury.

On turning the drum the space W enlarges, so that air is sucked through the opening f in the partition wall out of the front space V and, through the tube R, out of the receiver attached to the pump. As the turning continues the orifice f comes beneath the level of the mercury, and the air in the space W shut off in this way from the receiver, is forced into the channel c lying in the walls of the drum. Further turning forces the air from the channel into the space between the drum and the casing, when it is removed by an auxiliary pump, which must give so good a vacuum that the level of the mercury q outside the drum does not fall below the upper edge of the central opening.

From the description of the pump it will be seen that any substance which prevents the mercury from making air tight contact with the walls of the drum will lower the efficiency of the pump. Irregular particles of solid matter sticking to the porcelain will furnish an opportunity for air to remain behind and not be expelled, or to be carried in from the outside of the drum.

When an oil immersion pump is used for an auxiliary, the vapor from the oil diffusing into the Gaede pump is, I think, the chief cause of the loss in efficiency. This can be avoided to a certain extent by disconnecting the auxiliary when not in actual

use. The interior of the Gaede pump is shut off from the auxiliary by closing the steel cock h.

The McLeod gauge was needed in another part of the laboratory and so work was discontinued until fall.

When work was resumed, it was thought advisable to clean the pump, distill the mercury, and construct a new vessel for the gold leaves. The Hulett method[1] was used for distilling, the still being heated by Bunsen burners in an improvised asbestos furnace. It was suggested that I use an electrically heated furnace made by coiling wire in a box of sand. Such a furnace was constructed. A box 8"x 8" x5" was made of sheet steel, and was heavily lined inside and out with asbestos. Nickel wire, no. 12 B.S., was wound into a disc by the use of two cast iron plates which had been faced in the lathe and fastened on an arbor so that the distance between their faces was slightly greater than the diameter of the wire. The disc of wire was supported over the box by the larger outside coils, and the central portion, being unsupported, fell to the bottom of the box, forming a neat conical spiral about which sand was carefully packed. When completely covered the sand was removed from the center of the spiral, and the distilling flask was introduced. The ends of the wire were fastened to a small porcelain tube which was attached across the top of the box. This furnace worked excellently when the potential across the terminals was 220 volts. It was used but a short time when Dr. Knipp kindly offered to distill the mercury in a mercury arc still of his own design[2].

1 Phys. Rev., vol. CXVII, pp. 388, December, 1905.

2 Science, April, 1906.

The mercury in the pump was not distilled but was filtered through pin holes in a paper. The inside of the pump was carefully cleaned, but the inside of the drum was let alone because it is almost inaccessible and is easily broken.

The new form of electroscope is shown in Fig. 1, Plate III. It consists of a glass tube 4 cm. in diameter and 27 cm. long. One end was closed and the other drawn down so that it could be closed with a rubber stopper. Two windows were blown in the sides at the center as shown. The object of the windows was to get as thin glass as possible. The support for the gold leaves is shown separately at B. First a glass T was made, one arm of which had two platinum wires sealed into the ends, one of which made a support for the leaves. A copper wire connected the two pieces of platinum, thus the leaves could be earthed. Three small holes (c,d,f) were blown near the lower end of this arm to allow the vessel to be exhausted. After the leaves were put into the case, mercury was poured over the stopper to make an air tight seal.

This vessel was connected to the gauges, the gauges to a mercury "valve", (see Fig. 2, Plate III), and the valve to the Gaede pump.

The mercury valve is a U-shaped glass tube about 80 cm. long; at the curve a straight glass tube is connected which communicates with a mercury well through a rubber tube. By raising or lowering the well, the height of the mercury in the arms of the valve can be controlled. Near the top of each branch is a bulb to prevent the mercury from being thrown out by sudden changes in pressure. The valve thus made is gas tight and since it is of barometric height, will protect the system on either side against an accident

Plate III.

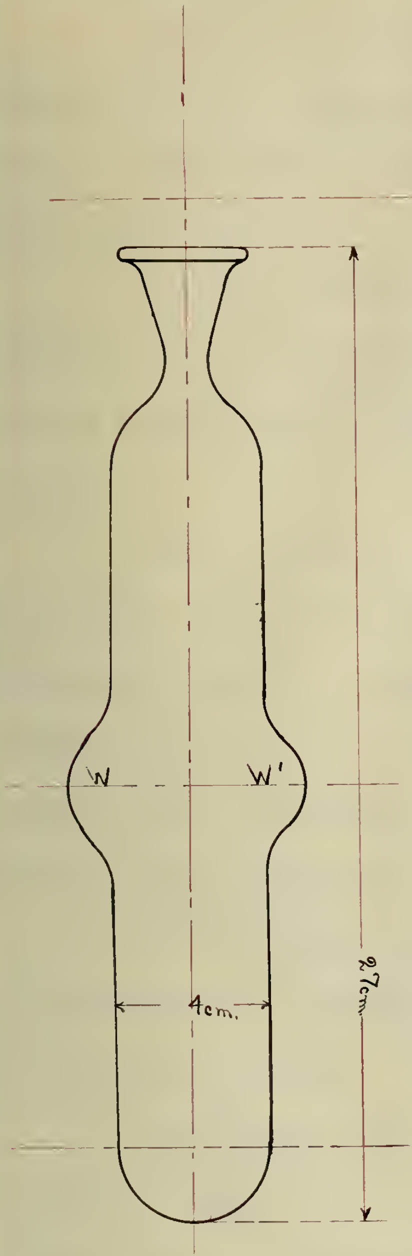
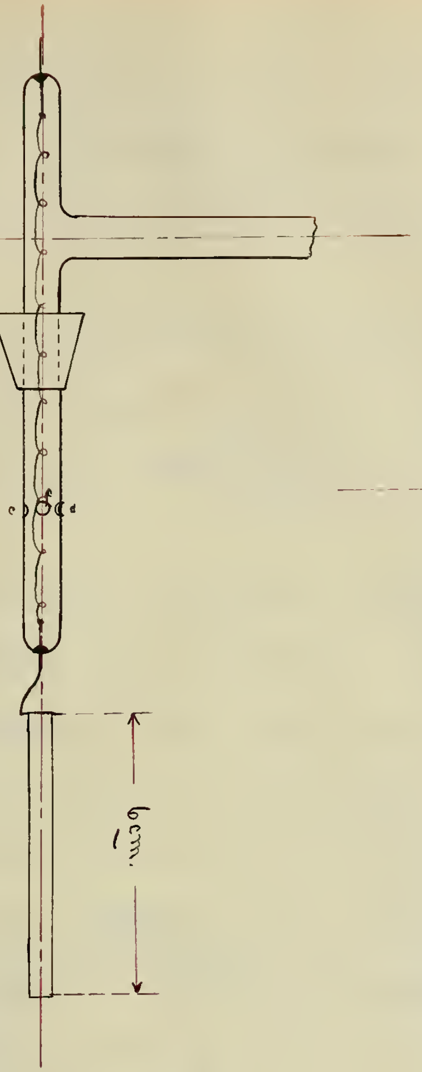


Fig. 1.



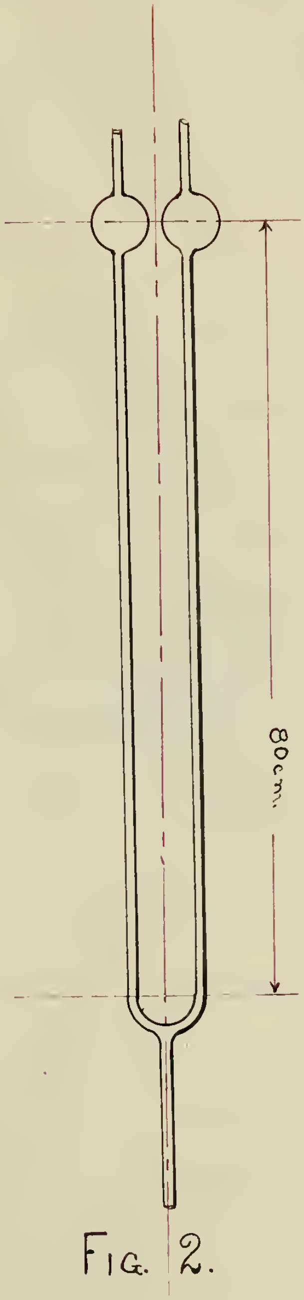


Fig. 2.

on the other side.

A 100 cc. gauge, made by J.W. Boehm, Chicago, was put in series with the large gauge. It measures pressures ranging from 4.5 mm. to 0.0005 mm. It was needed for pressures higher than the large gauge would measure.

After trouble with leaks around the ground glass joints on the pump had been stopped, the exhausted system was left standing two or three days to allow any gas that would leave the walls time to do so.

While working with leaks, I noticed a marked action of the leaves at higher pressures than I had expected. The divergence of the leaves due to a Bunsen burner 10 cm. away was 2 mm. when the pressure was 0.243 mm. At 0.008 mm. the divergence was 5 mm. The effect of an incandescent lamp (16 c.p.), of the Bunsen burner flame 10 cm. long, and of an ordinary gas flame all seemed the same.

Several days were spent trying to get an exhaustion as complete as earlier uses of the pump led me to believe it ought to give, but without success.

The Gaede pump was needed in an other part of the laboratory for two or three days, so I connected a Hemenway oil immersion pump to the gauges to see how low a pressure it would produce. Forgetting to close a valve that should have been closed, oil was slowly forced from the pump into the gauges. Very little of the mercury was contaminated by the oil, but the gauges had to be carefully washed. The shape and size of the McLeod gauge makes it very difficult to wash and to dry. The capillary tubes especially require careful attention.

The washing was done by using gasoline first, then a warm solution of potassium bichromate, dissolved in concentrated sulphuric acid. This was followed by potassium hydrate (KOH) which was care-

fully removed by washing with distilled water. The gauges were dried by forcing air from a foot bellows through a hot tube into them. The volume tube on each gauge required a capillary glass tube for introducing the acids, air, etc. In some way the inside of the volume tube on the large gauge must have been scratched, because, a few days after drying, a crack appeared which required that it be sent away for repairs.

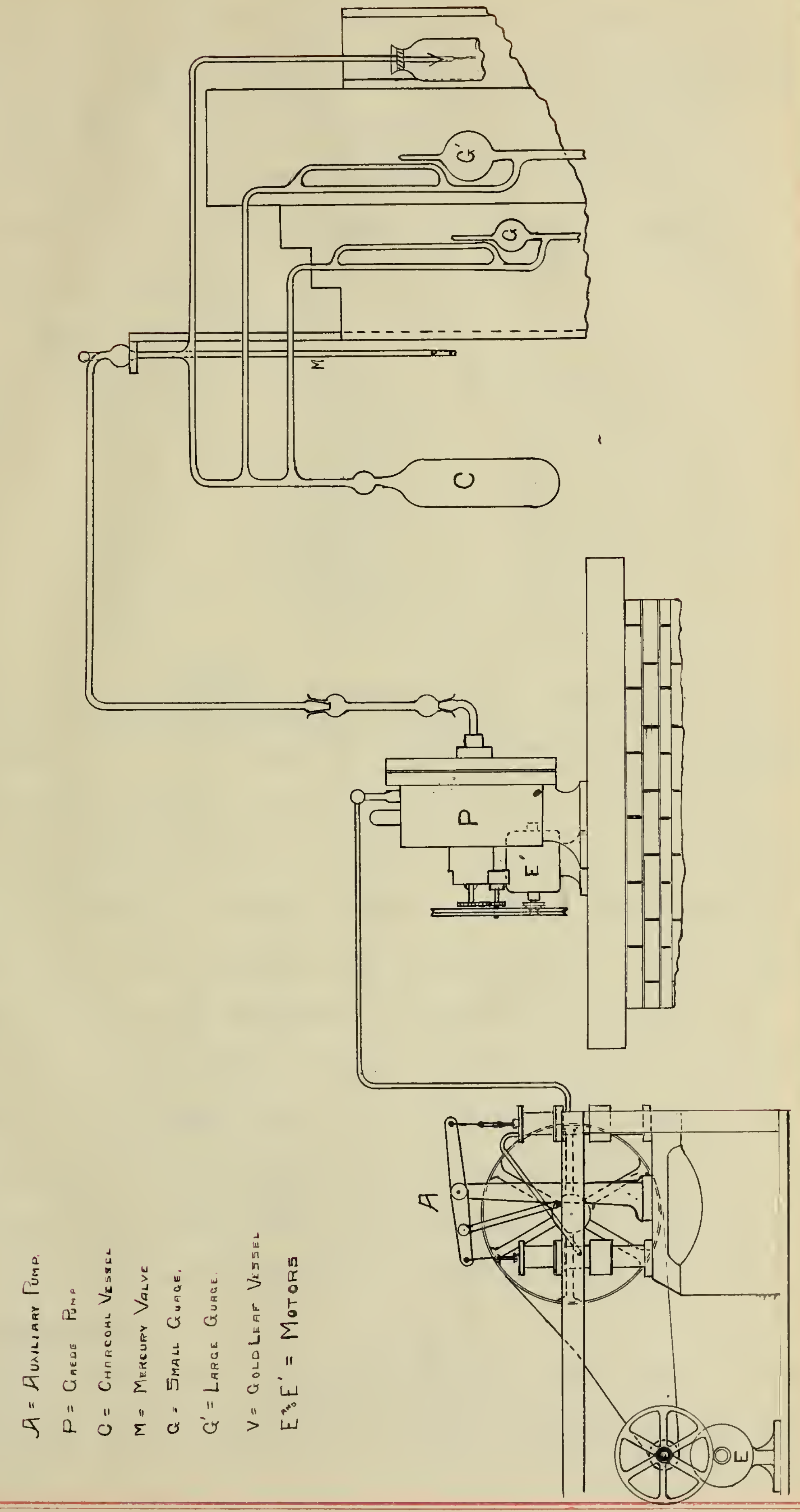
While waiting for the gauge to be repaired, all the apparatus was moved to another room, and a charcoal vessel was constructed to be used later for producing high degrees of exhaustion by Dewar's method.[1] For arrangement of the apparatus see Plate IV.

All connections were made with glass tubing which had an inside diameter of at least 3 mm. They were fused together and annealed in position. Rubber tubing connections, even though protected by mercury seals, were found unreliable. In Plate IV it will be noticed that the mercury valve was joined to the pump, next was the receptacle for the charcoal, followed by the two gauges to the larger of which the gold leaf vessel was attached. The only mercury seal in the system was the one closing the gold leaf vessel. There were three ground glass joints in the manometer portion of the pump, but when the mercury valve was closed, these were shut off from the highly exhausted part of the system.

When pressures as low as 0.001 to 0.0017 mm. were obtained and held for a week, I began a series of readings to determine the effect of change of pressure on the divergence of the leaves, and at what pressures the various sources of light and heat produced visible effects.

[1] Proceedings of the Roy. Soc., vol. 74, pp. 122-127.

Plate IV.


A = Auxiliary Pump.
P = Gaede Pump
C = Charcoal Vessel
M = Mercury Valve
G = Small Gauge.
G' = Large Gauge.
V = Gold Leaf Vessel
E and E' = Motors

The readings were made on a millimeter scale which was fastened onto the front of a plane mirror. The mirror was set behind the leaves so that a horizontal line on the scale was 5 mm. above the lower end of the leaves when they were together in a vertical position. Below is given a series of readings that show the change in divergence with the corresponding change in pressure.

Table IV.

Pressure tube	volume tube	pressure	divergence
12.0 cm.	0.22 cc.	0.334 cm.	1.0 mm.
1.7 "	0.10 "	0.17 "	3.0 "
4.2 "	0.05 "	0.141 "	4.0 "
0.5 "	0.10 "	0.005 "	8.0 "
2.3 "	0.05 "	0.0047 "	8.0 "
0.4 "	0.10 "	0.004 "	8.0 "
2.0 "	0.05 "	0.0022 "	7.5 "
3.0 "	0.10 "	0.003 "	7.5 "
1.9 "	0.05 "	0.0027 "	7.4 "

A repulsion as well as the divergence was observed at pressures below 0.003 mm., i.e., the leaf on the side away from the lamp moved farthest from the vertical position of the two. From the above readings it was noticed that the maximum divergence was between 0.004 and 0.005 mm. pressure. Several other series of readings were made at different times with slightly different results. Those that differed most gave a maximum divergence at pressures of 0.0027 and 0.0037 mm. The mean pressure given by all the readings was 0.0033 mm. Because the change in divergence was small for different pressures near that for the maximum effect, and because the fractions of millimeters were estimated, the data taken warrant only the conclusion that the maximum effect occurs at pressures between 0.002 mm. and 0.004 mm. mercury pressure.

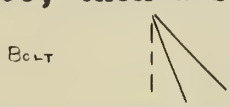
While taking the above readings it was observed that a divergence of the leaves could be detected at 2.5 mm. pressure for several

sources of heat and of light, and at 0.65 mm. for a test tube of water that had been frozen in liquid air.

At this time all of Bottomley's observations were verified except the effect of the hand when it alone is the source of heat. At no time could I detect any movement of the leaves due to the hand except when it was a screen cutting off light or heat radiation.

Some interesting observations were made while working with a rod of ice 2.5 cm. in diameter and 18 cm. long made by freezing a test tube of water in liquid air. When this rod of ice was brought near, with its axis parallel to the plane of the gold foil, the leaves diverged, the one nearest the ice moving most. The action of the leaves was very erratic. They sometimes slowly fell together, only to diverge again immediately. The amount of divergence was continually changing, and often they seemed to lose their activity after a few seconds exposure. By moving the ice parallel with its axis, it was found that some portions gave greater deflections than others. When one part of the ice failed to effect the leaves, another could be found that produced the usual divergence. The most active parts were always near one-third the length from either end, and when brought close to the case, the nearest leaf was drawn against the walls of the vessel.

Not enough data were taken to determine definitely why the action was so erratic, but it may have been due to the poor conductivity of the ice. This explanation was suggested by the action of a hot copper bolt. When heated to a red heat, 600 or 700°C., and brought near the leaves, the effects produced were always the same and very regular. There was first a divergence, then a slow repulsion of both leaves until they stood thus:



When the bolt was removed, the leaves immediately came together at

an angle of 30 to 40 degrees with the vertical and then they returned very slowly to their original position. At the time I did not think to try the bolt for its effects at liquid air temperature.

Because the ice at -150°C. produces as great a divergence as the bolt does at 700°C., one would expect that convection currents or other factors disturbing the distribution of heat would produce more marked effects in the case of ice.

At this time I began having trouble; the pressure could not be brought below 0.03 mm. It was thought that the charcoal was giving off gas, especially since a black deposit showed in several parts of the system. The gold leaves were black for half their length. Later I noticed that the mercury in the Gaede pump was low, and that, at a certain position of the drum, communication was made between the outer case and the vessels being exhausted. More mercury added to the pump prevented the communication but did not entirely remedy the trouble.

While trying to improve the vacuum, I took a great many readings to compare the gauges and to test for agreement of different parts of the scale for the same pressure. The data given in the following table shows how well the gauges agreed. Rather surprising since the large gauge was made by Max Kohl, Germany, and the small one by J.W. Boehm, Chicago.

Table V.

	pressure tube	volume tube	pressure
Small gauge	33.0 mm.	0.1 cc.	0.033 mm.
	-43.0 "	0.3 "	0.0339 "
	-11.0 "	0.2 "	0.0328 "
	34.0 "	0.1 "	0.0342 "
	16.0 "	0.05 "	0.00115 "
Large gauge	194.0 "	0.07 "	0.031 "
	160.0 "	0.08 "	0.0308 "
	112.0 "	0.10 "	0.0306 "
	6.0 "	0.04 "	0.00116 "

The lowest pressure obtained by the pump during this part of the work is given in Table VI. The table also shows the readings for the same pressure as given on different parts of the scale of the large gauge. The readings were taken first up, then down.

Table VI.

Pressure tube	volume tube	pressure
-59.0 mm.	0.14 cc.	0.00036 mm.
-49.7 "	0.12 "	0.0004 "
-29.2 "	0.08 "	0.00056 "
-10.0 "	0.04 "	0.00032 "
3.5 "	0.02 "	0.00032 "
16.0 "	0.01 "	0.00039 "
4.8 "	0.02 "	0.0005 "
-7.8 "	0.04 "	0.00042 "
-28.0 "	0.08 "	0.0008 "
-48.2 "	0.12 "	0.0007 "

The last two readings differ more than was the rule, but readings for very low pressures always varied more than for higher pressures as the following table will show.

Table VII.

Pressure tube	volume tube	pressure
11.0 mm.	0.14 cc.	0.0208 mm.
33.0 "	0.12 "	0.0202 "
59.5 "	0.10 "	0.0203 "
95.3 "	0.08 "	0.0205 "
147.2 "	0.06 "	0.0205 "
220.0 "	0.041 "	0.0192 "
149.0 "	0.06 "	0.02035 "
97.0 "	0.08 "	0.02036 "
60.5 "	0.10 "	0.0205 "
33.5 "	0.12 "	0.0211 "
12.0 "	0.14v "	0.0207 "

Throughout the work the gauges were unreliable for pressures lower than one ten-thousandth of a millimeter.

An effort was made to show that the action of the gold leaves is the same as that manifested in the Crookes' radiometer, and that it is dependent on the presence of a gas. A decidedly low pressure is required on account of the large surface and small mass of the

leaves.

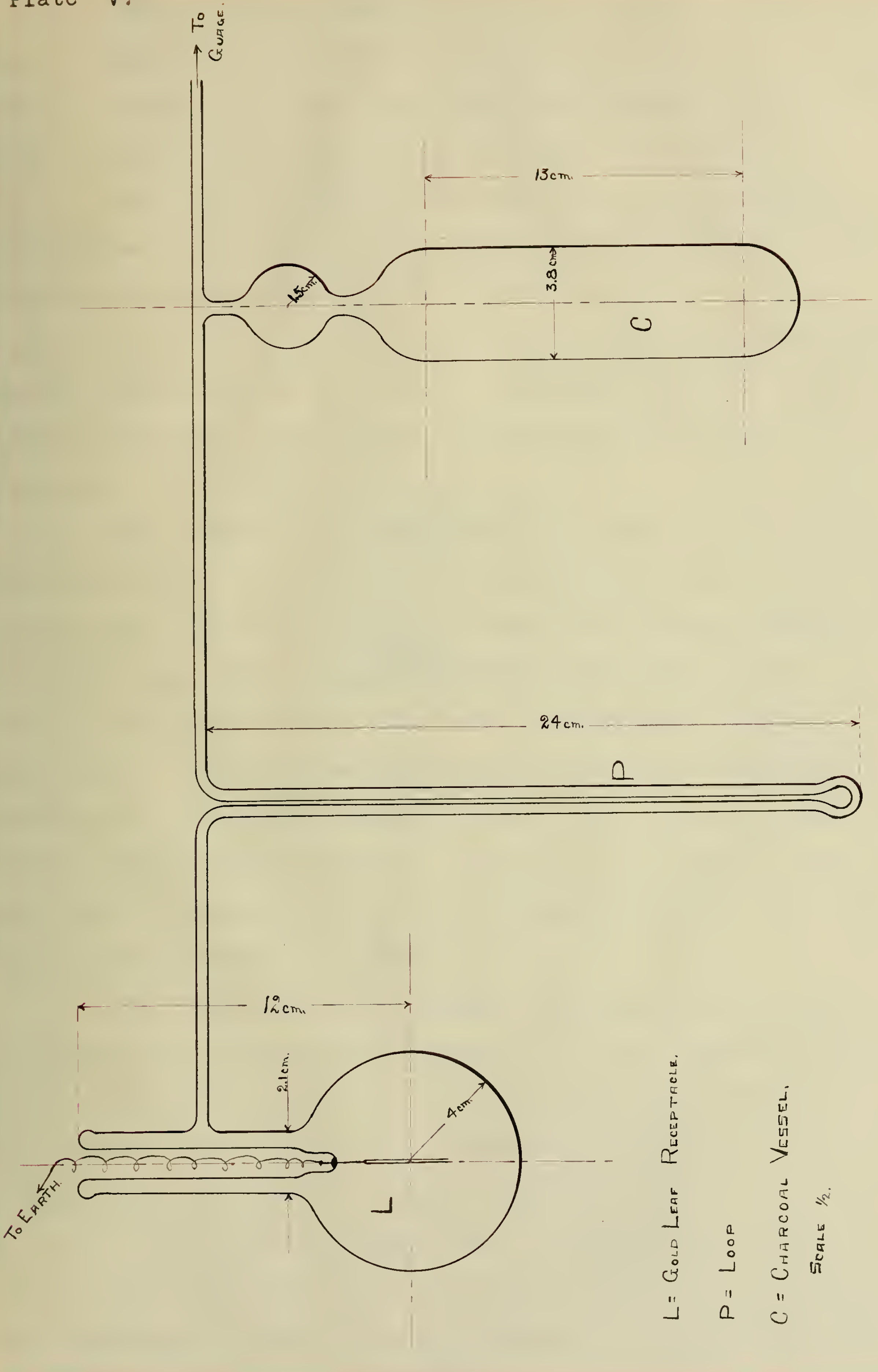
Because the gauges are not reliable for such low pressures, and because they offered a free mercury surface to supply mercury vapor beside adding 800 cc. volume, it was decided not to use them for this part of the work.

To be sure that the leaves were free from the presence of mercury vapor, the leaves and containing vessel were made new. The plan of the apparatus is shown in Plate V.

The vessel for the leaves was a 250 cc. spherical flask. A glass tube smaller than the neck of the flask, having a platinum wire sealed into the lower end to carry the gold leaves, was put into the flask and sealed at the top as shown. The gold leaves attached were 2 mm. wide and 3 cm. long. The exhaust tube was bent so that it formed a loop P that could be immersed in liquid air. Just beyond the loop is the receptacle C that contained the charcoal. The total volume of the part shown is 400 cc. Before sealing onto the gauge the loop P was immersed in liquid air and kept immersed until the observations were completed. The object of immersing the loop was to condense all moisture or mercury vapor before it reached the leaves.

Because charcoal does not absorb argon, helium, and the other inert gases in the air, it was desirable that they be removed if possible before the charcoal was immersed in liquid air. This is why the pump was used at all at this time. The method used in exhausting was the following; while the pump was running, the charcoal was heated until quite warm. The mercury valve was then closed and the charcoal allowed to cool. In cooling to room temperature, the pressure was reduced from 0.07 mm. to 0.02 mm. The system was left standing over night with the pressure as low as possible. The reading the next morning was such that it assured that there was no leak.

Plate V.



To Guage.
13cm.
3.8cm
1.5cm.
C
24cm.
P
12cm.
2.1cm.
4cm.
To Earth.
L
L = Gold Leaf Receptacle.
P = Loop
C = Charcoal Vessel.
Scale 1/2.

Before further pumping the air was allowed to enter the system slowly, past a sulphuric acid drier and over phosphorus pentoxide. The pump was then started and the pressure reduced to 0.05 mm., the charcoal having been heated during the pumping.

The vessel containing the leaves was heated to help drive any condensed gas from its walls, but the heating had to be done carefully and evenly for fear of tearing the leaves to pieces. A Bunsen burner left under the vessel burned with a flickering flame and the leaves took up the motion. The leaves took odd shapes and curious positions, depending on the position of the flame or on the direction of its motion.

The charcoal was heated while the pump was running, and when the pressure was 0.04 mm. the mercury valve was closed. The charcoal was cooled to room temperature; the pressure lowered to 0.003 mm. Again the charcoal was heated until the pressure was 0.153 mm. with the pump running. The mercury valve was closed and the charcoal cooled. The pressure resulting was 0.003 mm. This was done to obtain some idea of the pressure limits that could be gotten in the vessel without using liquid air. By heating the charcoal the pressure could be raised to 0.045 mm., and when cooled to room temperature the pressure was 0.003 mm.

The charcoal was now heated, the mercury valve closed, and the seal made. When cool the charcoal bulb was immersed in liquid air and the following data taken as the divergence due to a 16 c.p. incandescent lamp clamped 10 cm. away. The readings were made from a paper scale fastened to a mirror, and set behind the leaves so that a line on the scale when viewed over a straight-edge strikes the leaves 5 mm. above the lower end. The readings are the positions of the right and left leaf, with the corresponding time after the char-

coal was immersed.

Table VIII.

Left leaf	right leaf	time	divergence
3.55	3.10	8:54	0.45
3.55	3.10	8:58	0.45
3.55	2.99	9:00	0.56
3.55	2.99	9:01	0.56
3.52	2.89	9:015	0.63
3.50	2.88	9:02	0.62
3.50	2.91	9:03	0.59
3.50	2.92	9:04	0.58
3.49	2.94	9:05	0.55
3.48	2.95	9:06	0.54
3.47	2.94	9:07	0.53
3.48	2.92	9:08	0.56
3.47	3.00	9:10	0.47
3.46	3.02	9:11	0.44
3.43	3.04	9:12	0.39
3.41	3.10	9:14	0.31
3.40	3.15	9:20	0.25
3.40	3.20	9:22	0.20
3.39	3.24	9:24	0.15
3.38	3.24	9:25	0.14
3.38	3.25	9:27	0.13
3.38	3.26	9:30	0.12

Because the leaves were so close together further readings of their positions were not made, but they were carefully watched until an opaque body swinging to and fro between the lamp and the leaves produced no visible effect. This was found to be the most sensitive method for detecting an action of the leaves. It was 45 minutes after starting to immerse the charcoal in liquid air before I could be sure that the effect of the lamp was entirely destroyed.

The arc light was now thrown on the leaves and when focused by a lens with a 15 cm. focal length and with a diameter of 8 cm., produced a deflection of 8 mm. 30 minutes later all effect of the focused light had died out, although it was so intense that the hand was burned by focusing the light on it. A second trial showed that with the charcoal at room temperatureat the beginning, 40 minutes were necessary for all action of the lamp to be destroyed, and 95

minutes for all visible effect of the focused arc light to be destroyed.

I had intended doing further work with the vessel as now exhausted but in a few days after the loop had been removed from the liquid air, the leaves were almagated and soon dropped to the bottom of the flask.

Dewar in one of his reports[1] gives the following data. 5 grams of charcoal were used in a 300 cc. volume. The time after the charcoal was immersed in liquid air is given in the first column, and the corresponding pressure in the second.

Table IX

Time		pressure	
0.0	min.	1.6445	mm.
5.0	"	0.0545	"
10.0	"	0.0132	"
30.0	"	0.000139	"
60.0	"	0.000047	"

The ratio by weight of charcoal used to the volume of gas is four or five times as great, and the initial pressure only one fortieth as great in the present experiment as in the one quoted. Assuming that the absorbtion of gas by the charcoal is proportional to its mass, then, even if the rate falls off considerably with the reduced pressure, the exhaustion when the leaves failed to respond was probably as low as 0.0000005 mm.

Nichols and Hull[2] in measuring radiation pressure with a special form of the radiometer have shown that the forces acting on an illuminated body are two; first, the attraction or repulsion due to the action of the gas molecules surrounding the body, and second, the radiation pressure. They also showed that beginning with a gas

1 Engineering, vol. 83, pp. 781-782, June 14, 1907.

2 Phys. Rev. vol. 13, pp. 307, 1901, also vol. 17, pp. 26, 1903.

pressure of 60 mm. the gas action was a repulsion changing to a suction in passing from 19.8 to 11.2 mm. For low pressures the suction increases to 0.05 mm. At a gas pressure of 0.02 mm. the gas action is again a strong repulsion.

Summary —— All of the observations made by Bottomley were repeated and verified except the effect due to the presence of the hand when acting as an exciting source. It produced an effect only when acting as a screen to shut off radiations.

I also found that the leaves are not nearly so sensitive at the pressure he gives as they are at pressures considerably higher.

A divergence was observed at pressures as high as 2.5 mm. for light and heat sources, and at 0.65 mm. for ice produced by liquid air. Ice at 0.0°C. did not effect the leaves.

The divergence due to heat and light sources as the pressure was reduced from 2.5 to 0.0000005 mm. showed an increase until the pressure was 0.02 to 0.03 mm., after which it decreased for a time, then increased again until it was a maximum at 0.002 to 0.004 mm. For lower pressures the divergence gradually decreased to zero. The variation in the divergence, and the fact that it was destroyed by very low pressures was, I think, conclusive proof that the action was dependent on the presence of a gas in the inclosing vessel and was the radiometric action as manifested in the Crookes' radiometer.

I wish to thank Professor Carman and Dr. Knipp for their interest and help in the work. To Dr. Knipp, I owe the difficult work in glass blowing and an immense saving of time in distilling mercury and preparing liquid air.